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ANALYSIS OF EMP RESPONSE OF STRUCTURES USING FREQUENCY DOMAIN ELECTROMAGNETIC INTERACTION CODES

by

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ABSTRACT

This report concerns the use of frequency domain computer codes such as the Numerical Electromagnetic Code (NEC) for computing the time domain Electromagnetic Pulse (EMP) response of structures such as antennas, aircraft or communication shelters. The proper representation of the EMP excitation and the selection of a number of appropriate frequencies to obtain a correct time domain EMP response are studied. The effects of adapting the modelling of the problem for different frequency ranges is discussed. Guidelines are given for obtaining a correct time domain response with efficient use of computer time.

RÉSUMÉ

Ce rapport considère l'utilisation de programmes calculant la réponse en fréquence de systèmes tels que des antennes, des avions ou des systèmes de communications pour obtenir la réponse temporelle résultant d'une excitation de type IEM (impulsion électromagnétique). Les conséquences d'une représentation approprié de l'excitation IEM ainsi que de la sélection d'un certain nombre de fréquences pour calculer la transformée de Fourier inverse sont étudiées. Quelques règles simples sont données pour obtenir une réponse temporelle exacte tout en utilisant le minimum de temps calcul.

EXECUTIVE SUMMARY

The Electromagnetic Pulse (EMP) interaction analysis is an important part of the recommended procedure for hardening electronic equipment against the effects of EMP generated by a nuclear detonation. This report concerns the use of frequency domain computer codes such as the Numerical Electromagnetic Code (NEC) for computing the time domain EMP response of structures such as antennas, aircraft or communication shelters.

Some properties of the Discrete Fourier transform (DFT) and the Fast Fourier transform (FFT) and some of their side-effects when applied to solve time domain problems are discussed. A technique using cubic-spline interpolation to perform a DFT or a FFT on unevenly spaced sequences is introduced.

The effects of the choice of a proper model for the EMP excitation and of the selection of an appropriate number of frequencies for taking an inverse Fourier transform for obtaining a correct time domain EMP response are studied. Comparisons are made between the results obtained by the Fourier transformation of the frequency domain results and those obtained with a time domain code such as the Thin Wire Time Domain code (TWTD). General guidelines are given for obtaining a correct time domain response with efficient use of computer time.

TABLE OF CONTENTS

		PAGE
ABSTRACT		iii
EXECUTIVE SUMMARY		v
TABLE OF CONTENTS		vii
1.0	INTRODUCTION	1
1.1	EMP ANALYSIS AND HARDENING	1
1.2	EMP NUMERICAL ANALYSIS CODES	1
1.3	ELECTROMAGNETIC INTERACTION CODES	2
1.3.1	Thin Wire Time Domain Code	2
1.3.2	Numerical Electromagnetic Code	3
1.3.3	Electric-Field Integral Equation Code	3
1.3.4	General Electromagnetic Model for Analysis of Complex Systems	3
2.0	THE DISCRETE FOURIER TRANSFORM	5
2.1	GENERAL PROCEDURE	5
2.2	THE DISCRETE FOURIER TRANSFORM ALGORITHM	5
2.3	THE FAST FOURIER TRANSFORM ALGORITHM	7
2.4	RELATIONSHIPS BETWEEN THE DFT AND THE FOURIER TRANSFORM	8
3.0	SOLVING TIME DOMAIN PROBLEMS WITH THE DFT	11
3.1	EMP WAVEFORM DEFINITION	11
3.2	MINIMIZING THE COMPUTATION TIME FOR FREQUENCY DOMAIN CODES	16
3.3	SELECTION OF AN ADEQUATE FREQUENCY STEP	16
3.4	SELECTION OF AN ADEQUATE FREQUENCY RANGE	19
3.5	INTERPOLATION OF THE FREQUENCY RESPONSE	19
3.6	SMALL STRUCTURES	23
4.0	CONCLUSIONS	27
APPENDIX A		29
APPENDIX B		33
B.1	GUIDELINES FOR SOLVINS TIME DOMAIN PROBLEMS	33
B.2	GUIDELINES FOR INTERPOLATING THE FREQUENCY DOMAIN TRANSFER FUNCTION	33
B.3	GUIDELINES FOR PERFORMING THE DFT AND FFT ALGORITHMS	34
REFERENCES		35

1.0 INTRODUCTION

This report concerns the use of frequency domain computer codes such as the Numerical Electromagnetic Code (NEC) for computing the time domain Electromagnetic Pulse (EMP) response of structures such as antennas, aircraft or communication shelters. The effects of the choice of a proper model for the excitation and of the selection of an appropriate number of frequencies for taking an inverse Fourier transform and obtaining a correct time domain EMP response are studied. Guidelines are given for obtaining a correct time domain response with efficient use of computer time. Validation of this technique is obtained by comparing the results of a frequency domain code with those of a time domain code as well as with experimental results.

1.1 EMP ANALYSIS AND HARDENING

Electromagnetic pulse resulting from a nuclear detonation, usually referred to as EMP, is one of the most serious nuclear effects, since it can adversely affect performances of electronic and weapon systems hundreds of kilometres away from the source. The EMP is a high-intensity, short-duration electromagnetic field and although its energy content is not very large because of its short duration, electronic components or systems can be upset or permanently damaged by the very high voltages or currents which can be induced and coupled into the system. Analytical tools and methodology have been developed to assess EMP vulnerability and obtain EMP hardness of a system. Different EMP simulators and test procedures have also been developed to ensure EMP hardness.

Hardening against EMP is an iterative process where the EMP interaction with the system is predicted, the effectiveness of the shielding, filters, and other protective components is estimated, and induced voltages or currents reaching sensitive components are checked against their upset or damage threshold. EMP testing is performed to increase confidence that system hardening has been properly addressed. Susceptibilities discovered during analysis or testing are corrected with hardening techniques, such as shielding and filtering.

1.2 EMP NUMERICAL ANALYSIS CODES

The complete problem of the coupling of the EMP from a specific detonation into the components of a specific system is an extremely complex problem. There are no existing computer codes which can treat the complete problem, and as a consequence, various aspects of the EMP problem are studied individually with the aid of the existing codes. Good engineering practices must then be used to combine the various parts of the solution into an assessment of the EMP vulnerability.

The various computer codes available can be divided into three general classes: environment codes, coupling codes, and circuit-analysis codes. The environment codes calculate the electromagnetic fields generated by a nuclear detonation. The coupling codes determine the currents, potentials, and charges induced into isolated bodies and transmission lines by incident electromagnetic fields. The circuit-analysis codes analyze the response of linear and nonlinear circuits to voltage and current injections resulting from EMP illumination.

The environment codes are used to predict the electromagnetic fields generated by nuclear detonations and usually require in-depth knowledge of a weapon. For practical engineering practices, the EMP environment is usually specified for various type of equipments or installations in standards documents, such as [2].

The electromagnetic interaction coupling codes are used to calculate the charges and currents induced in structures or transmission lines by an incident pulse and estimate the field penetration through apertures or shielding. Designers of those codes have taken different mathematical or numerical approaches [5] which make them better suited for certain type of structures or problems. The interaction codes can be divided into two general categories: frequency domain codes and time domain codes. Frequency domain codes evaluate the currents and charges induced at a specified frequency. A large number of frequencies is required in order to estimate the time domain response of the system from its frequency response. Time domain codes compute the time response directly, which make them more suitable to solve EMP problems. However, in many cases, a time domain code suitable to solve a particular problem does not exist and a frequency domain code must be used.

The circuit-analysis programs, such as SPICE or MICRO-CAP, are primarily nonlinear, transient-analysis codes. Some will also perform AC, DC, and frequency-analysis calculations. They do not compute the coupling of the EMP transient fields into the circuit directly and thus rely on other codes to provide the EMP coupling, usually as voltages or currents as functions of time. Performances of protective devices, such as arrestors and filters, can be evaluated to predict the currents or voltages reaching sensitive components of a system.

1.3 ELECTROMAGNETIC INTERACTION CODES

This section briefly describes several interaction codes that are currently in use at DREO or being implemented. A frequency domain, NEC, and a time domain code, TWTD, were chosen to conduct this study to obtain comparative data between the two methods. All computer simulations were executed on a VAX 11/780 or on a MicroVAX-II. All execution times (CPU time) given are normalized for a MicroVAX-II.

1.3.1 Thin Wire Time Domain Code

The Thin-Wire Time-Domain code (TWTD) [6] is a time domain computer code to compute the induced currents on, and the radiated or scattered fields from an arbitrary thin wire antenna or structure. The excitation on the structure is a specified time-varying source or an incident plane wave. The output may include currents, the radiated or scattered fields, antenna gain, and the spectral characteristics of the input impedance. Although TWTD analyzes only structures in free space, structures over perfect ground can be analyzed by explicitly using image theory. The code was modified to accommodate larger structures or longer time history and to define new excitations specific to EMP studies.

1.3.2 Numerical Electromagnetic Code

The Numerical Electromagnetic Code (NEC) [7] is a frequency domain computer code for the analysis of the electromagnetic response of antennas and other metal structures. The code combines formulation of smooth surfaces and wires for convenient and accurate modelling of a wide variety of structures. A model may include nonradiating networks and transmission lines connecting parts of the structure, perfect or imperfect conductors, and lumped-element loading. A structure may also be modeled over a ground plane that may be either a perfect or a imperfect conductor. The excitation may be either voltage sources on the structure or an incident plane wave. The output may include the induced currents and charges, the near electric or magnetic fields, and the radiated fields.

NEC is probably one of the most versatile code available today. NEC has been used for many radiation and scattering problems. Its use for EMP coupling problems has been less common because of the large amount of computing time required for the determination of currents on a complex structure for a large number of frequencies.

1.3.3 Electric-Field Integral Equation Code

The Electric-Field Integral Equation Code (EFIE) [8] is a frequency domain computer code developed to treat the problem of electromagnetic scattering from arbitrarily shaped, perfectly conducting objects, illuminated by an incident plane wave. Objects are modelled with triangular surface patches which may include apertures or cavities. The program computes the surface current density induced on either an open or closed surface as well as the bistatic radar cross section of the object. The code was modified in house to compute also the field intensities from the current densities on the surface. There have been other major modifications made to produce drastic reduction in computing time.

1.3.4 General Electromagnetic Model for Analysis of Complex Systems

The General Electromagnetic Model for Analysis of Complex Systems (GEMACS) incorporates a variety of techniques for electromagnetic analysis of complex objects. The latest available version of the code includes thin wire and surface patch Method of Moments (MOM) formalism, with or without Geometrical Theory of Diffraction (GTD) interactions, to solve for exterior problems. It also includes a Finite Difference (FD) formalism in the frequency domain to solve interior problems and mathematics necessary to connect exterior and interior solutions when apertures are present.

2.0 THE DISCRETE FOURIER TRANSFORM

The procedure described in this report is used to solve time domain problems. It is based essentially on computing the frequency domain representation of the solution and applying an inverse discrete Fourier transform algorithm to obtain the time domain solution. This chapter introduces the general procedure used to obtain the solution and provides a detailed description of discrete Fourier transform and its properties.

2.1 GENERAL PROCEDURE

A time domain analysis code, if one is available to solve a particular problem, is usually more efficient to compute time domain solutions. In many cases however, the only choice is to use a frequency domain analysis code. Many frequency domain codes have been developed to solve radiation and scattering problems. Some of them, such as NEC, are very versatile and can be used to model a large variety of problems.

A linear time-invariant system can be fully characterized by its transfer function $H(\omega)$. A frequency domain analysis code can be run at multiple frequencies to compute $H(\omega)$. The response $y(t)$ of a system to a known excitation $e(t)$ can be expressed in frequency domain as:

$$Y(\omega) = H(\omega) \cdot E(\omega) \tag{1}$$

where $E(\omega)$ and $Y(\omega)$ are the Fourier transform of $e(t)$ and $y(t)$ respectively and $H(\omega)$ is the numerically computed transfer function. For our purpose, the excitation $e(t)$ is known and its Fourier transform can be evaluated analytically. The solution $y(t)$ is obtained with the inverse Fourier transform of $H(\omega) \cdot E(\omega)$:

$$\begin{array}{ccc} e(t) & \Rightarrow & E(\omega) \\ & & \cdot \\ & & H(\omega) \\ & & \Downarrow \\ y(t) & \Leftarrow & Y(\omega) \end{array} \tag{2}$$

This procedure involves using a frequency domain code such as NEC to compute the frequency response $H(\omega)$. This is very computationally intensive, easily taking several days of CPU time to complete. In addition, the transfer function is not computed in its continuous form, but rather at a number of discrete frequencies. Consequently, the discrete form of the Fourier transform (DFT) must be used. Some of the DFT properties must be understood to avoid some 'side-effects' when used. Guidelines to minimize the number of frequencies and CPU time required will be presented in Chapter 3.

2.2 THE DISCRETE FOURIER TRANSFORM ALGORITHM

The Fourier transform (FT) of a continuous waveform is a continuous-frequency signal representation of its spectrum or frequency content. However,

when a waveform is sampled, which is necessary when the system is to be analyzed on a computer, its discrete counterpart, the discrete Fourier transform (DFT) must be used. The DFT retains most of the properties of the continuous Fourier transforms. There are however some important differences which may cause the DFT to produce erroneous results. Some properties more relevant to our application will be discussed here. Many text books treat the FT and the DFT in more detail [16] [11] [12] [13].

The Fourier transform and its inverse are defined as:

$$X(f) = \int_{-\infty}^{\infty} x(t)\, e^{-j2\pi ft}\, dt \tag{3}$$

and

$$x(t) = \int_{-\infty}^{\infty} X(f)\, e^{j2\pi ft}\, df \tag{4}$$

As observed in equations (3) and (4), some symmetry or duality exists between the two equations. This duality can be formulated as:

$$\begin{aligned} &\text{if} && x(t) \rightarrow X(f) \\ &\text{then} && X(t) \rightarrow x(-f) \end{aligned} \tag{5}$$

This duality implies that every property of the Fourier transform is also applicable to its inverse. It follows that if there are characteristics in time domain which have implications in frequency domain, then the same characteristics in frequency domain will have similar implications in time domain.

The discrete form of the Fourier transform (DFT) and its inverse (IDFT) are defined as[1]:

$$X(k) = \sum_{n=0}^{N-1} x(n)\, e^{-j2\pi kn/N} \tag{6}$$

and

$$x(n) = \frac{1}{N} \sum_{k=0}^{N-1} X(k)\, e^{j2\pi kn/N} \tag{7}$$

where x(n) is a real sequence[2] of N points representing a waveform sampled at a regular interval Δt and X(k) a complex sequence of N points representing its transform at frequencies 0, f_0, $2f_0$, ... , $(N-1)f_0$. It is clear from these definitions that both sequences X(n) and X(k) are periodic with a period of N samples. A consequence of this periodicity is that shifting a sequence always implies a circular shift. The effect of this property in time domain is that

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[1] The definition of the DFT is not uniform in the literature. The 1/N factor is sometime placed in the X(k) definition.

[2] In general, the sequence x(n) can be complex. In our case however, the solution is known to be real as it represent a measurable quantity (current or voltage).

when shifting a sequence, the end of the waveform wraps-around its beginning. The effect in frequency domain is that the sequence appears to have been mirrored around N/2 when in fact the frequencies at k=N to N/2 are the negative frequencies of the transform from $-\Delta f$ to $-f_{max}/2$.

It can be derived from the symmetry property of the Fourier transform that if x(n) is real, then

$$X(k) = X^*(-k) \tag{8}$$

where X^* denotes the conjugate. It states that before a time domain sequence can be reconstructed, the frequency response obtained from the simulations must be first mirrored with its conjugate.

The sampling interval Δt and the fundamental frequency f_0 or Δf do not appear explicitly in equations (6) and (7). The time and frequency scaling property of the Fourier transform

$$x(at) \leftrightarrow \frac{1}{|a|} G\left(\frac{f}{a}\right) \tag{9}$$

can be applied to adjust the amplitude and calculate the interval of the sequences. It follows that:

$$\Delta t = \frac{1}{N\Delta f} \quad \text{and} \quad \Delta f = \frac{1}{N\Delta t} \tag{10}$$

and

$$t_{max} = (N-1)\Delta t \approx \frac{1}{\Delta f} \quad \text{and} \quad f_{max} = (N-1)\Delta f \approx \frac{1}{\Delta t} \tag{11}$$

For EMP problems, a finite duration excitation yields a finite duration response. Consequently, the frequency sampling Δf must be small enough to translate into a sufficient time duration t_{max}. Similarly, Δt must be small enough to capture the fastest transitions of the solution, imposing a sufficient frequency range f_{max}, or for a given Δf, a sufficient number of frequencies N.

A common technique used with the DFT consists in extending a sequence x(n) of N points to M points by adding zero-valued samples at the end (zero-filling). It can be easily demonstrated from equations (6) and (7) that this allows one to compute the transform at arbitrary resolution, effectively yielding exact interpolation between points. This property is most useful to fit the length of the sequence to meet the limitations of some of the practical DFT implementations.

2.3 THE FAST FOURIER TRANSFORM ALGORITHM

The fast Fourier transform (FFT) is merely a very clever implementation of the DFT. For a sequence of N points, the execution time is proportional to $4N^2$ for the DFT compared to $N/2 \cdot \log_2 N$ for the FFT. For a 1024 points sequence, the FFT algorithm is over 800 times faster. The original FFT implementation [14] was

chosen, with few modifications to take into account the scaling due to Δf as defined by equation (9). A listing of the subroutine is given in Appendix A. The only restriction with this algorithm is that the size of the sequence is restricted to powers of 2 ($N=2^m$). A more exhaustive overview of alternate implementation of the FFT can be found in [15].

2.4 RELATIONSHIPS BETWEEN THE DFT AND THE FOURIER TRANSFORM

Whenever the IDFT is used to reconstruct a continuous waveform from its frequency domain definition, a set of operations, whether they are implied or explicit, are performed, each altering the result. To illustrate the most common problems with the DFT (aliasing, leakage, etc.), consider a waveform y(t) derived from its known Fourier transform Y(f), as shown on Figure 2-1(a).

The transform Y(f) is computed from numerical simulations, at a number of equally spaced frequencies. This corresponds to multiplying Y(f) with a Dirac comb function, with a period of Δf. The transform to time domain of this comb function is also a comb function with a period of $1/\Delta f$ (Figure 2-1(b)). Multiplication in frequency domain yields a convolution in time domain, resulting in y(t) becoming periodic and being corrupted with aliasing (Figure 2-1(c)). The only method to reduce the aliasing is to decrease Δf.

Only a finite portion of Y(f) is computed, for frequencies from 0 to f_{max}, thus ignoring some higher frequencies. This is equivalent to multiplying Y(f) with a rectangular window W(f), of width $\pm f_{max}$. As observed on Figure 2-1(d), the rectangular window has a transform in the form of a sin(x)/x function. When Y(f) is convolved with the window's transform, some leakage effect can be observed (Figure 2-1(e)). This effect can be reduced by increasing f_{max}, and thus N, or the using a different window, such as a cosine-tapered window. The combined effect of the sampling and windowing is shown on Figure 2-1(f).

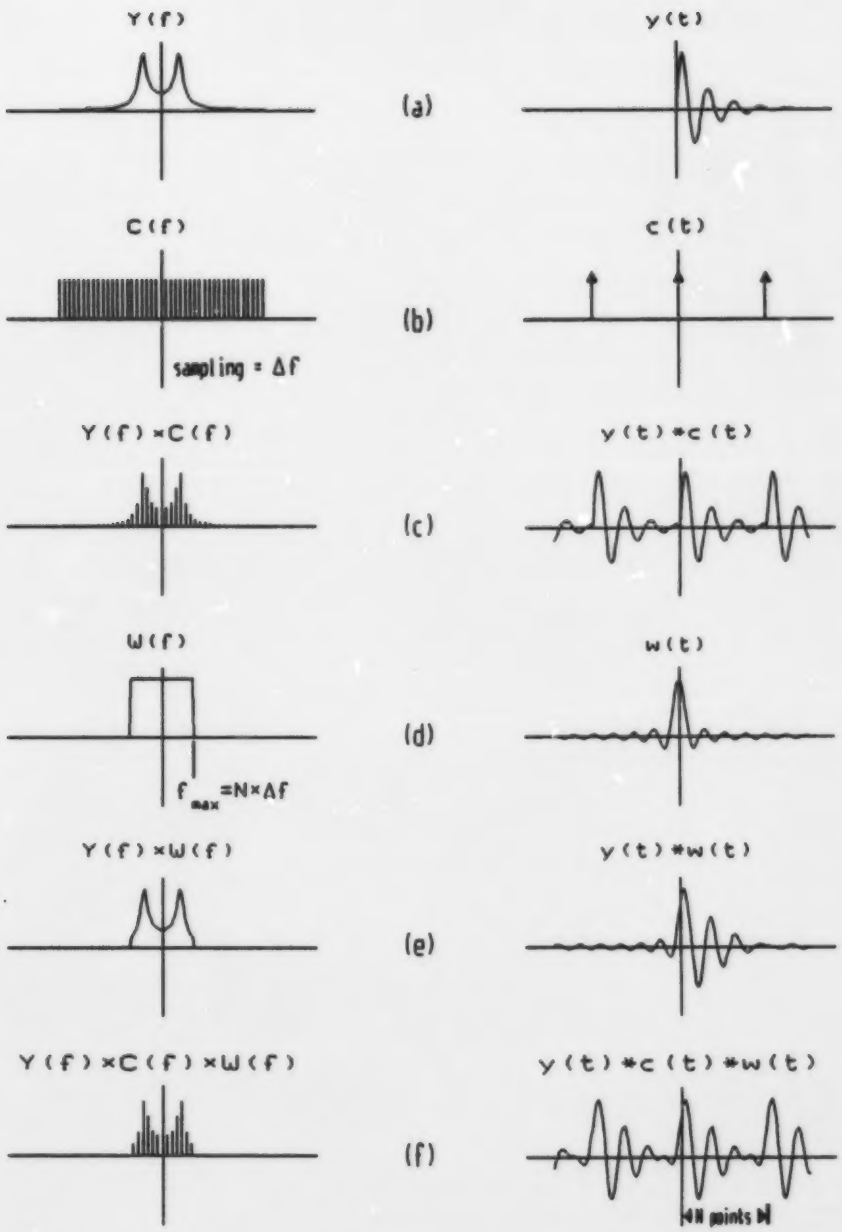

Figure 2-1 Illustration of some of the properties of the discrete Fourier transform.

3.0 SOLVING TIME DOMAIN PROBLEMS WITH THE DFT

The procedure described to obtain a time domain solution by taking the inverse discrete Fourier transform of a computed frequency domain solution is relatively simple. However, in the absence of any guidelines, this process can be very time consuming and lead to erroneous results. Simple guidelines will be developed in this chapter to obtain an accurate time domain solution with the efficient use of computer time.

To illustrate some of the techniques presented in this chapter, a sample problem will be used. Figure 3-1 shows a stick model of a helicopter. It is a crude wire grid representation of it, consisting of 185 segments. The currents induced from an incident EMP waveform were computed with a time domain code (TWTD) and with a frequency domain code (NEC). In this example, it took NEC over 136 hours on a MicroVAX II to compute the currents at 1024 frequencies, 0.25 MHz apart, giving the frequency response of the system as shown on Figure 3-2, necessary to obtain an accurate time domain response, shown on Figure 3-3. It took TWTD about 2.5 hours to compute a solution, but due to code limitation, only the first 400 ns were obtained. Nevertheless, the agreement with NEC is very good, as shown on Figure 3-4. This solution will be used thorough this chapter as a point of comparison to evaluate the effect of various parameters.

3.1 EMP WAVEFORM DEFINITION

The EMP produced by a nuclear burst at high altitude is a large-amplitude, very short duration transient field covering a very wide area beneath the burst point. In general, the exact characteristics of the EMP field such as peak amplitude, rise time and polarization, depend on many factors, such as the weapon yield, the height of burst and the observer's location. For practical purposes, a standard waveform representing a worst case is used [2] [3].

The simplest analytical expression approximating the EMP waveform, often referred to as the Bell curve [4] or the *old* NATO definition, is the double exponential waveform:

$$E(t) = AV \cdot (e^{-\alpha t} - e^{-\beta t}) \tag{12}$$

As shown in Figure 3-5, this pulse has a peak value of 50 kV per meter, a rise time (10-90%) of about 4.2 nsec, a pulse width (50-50%) of about 185 nsec and a decay time (peak-to-10%) of about 600 nsec. This expression is very useful due to its simplicity. Its Fourier transform:

$$E(\omega) = AV \cdot \left(\frac{1}{\alpha + \omega j} - \frac{1}{\beta + \omega j}\right) \tag{13}$$

and its Laplace transform are very simple, which makes it possible to solve simple problems analytically. However, this expression has a major flaw which can render the results of a numerical simulation useless. As observed in Figure 3-5, the waveform is continuous over time, but its first derivative is discontinuous at $t = t_0$. Since the coupling of electromagnetic waves to a structure is strongly dependent of the derivative of the excitation, this

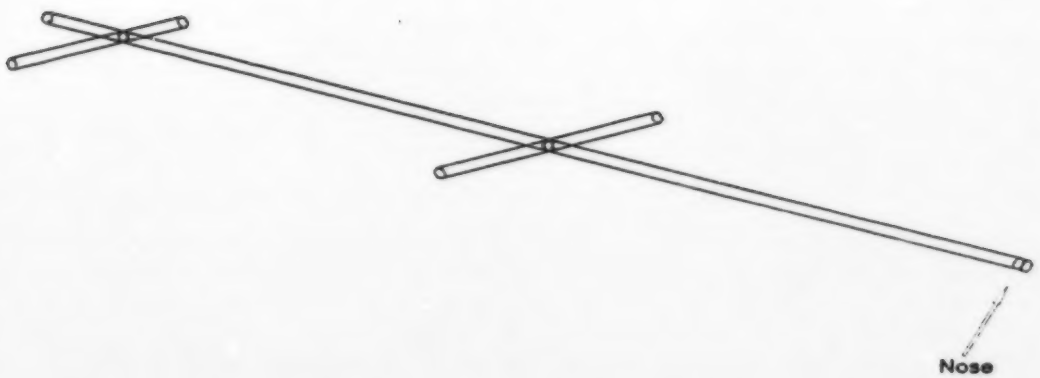

Figure 3-1 Stick model of a helicopter, consisting of 185 thin wire segments. The model is about 19.5 meters long. Calculations were made with NEC and TWTD to estimate the current at the nose (segment on the right).

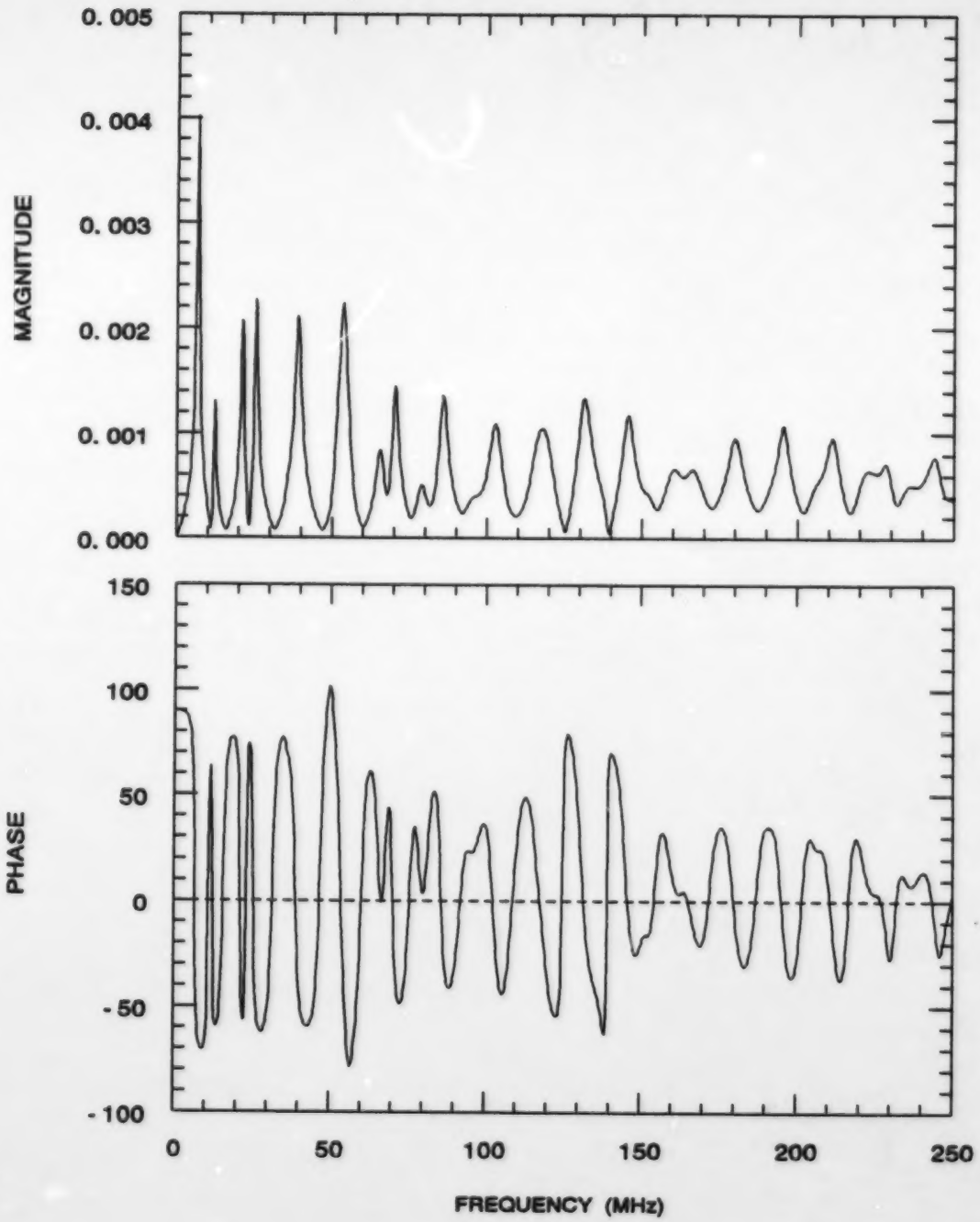

Figure 3-2 Transfer function (magnitude and phase) at the nose of the stick model helicopter, computed by NEC at 1024 frequencies, 0.25 MHz apart.

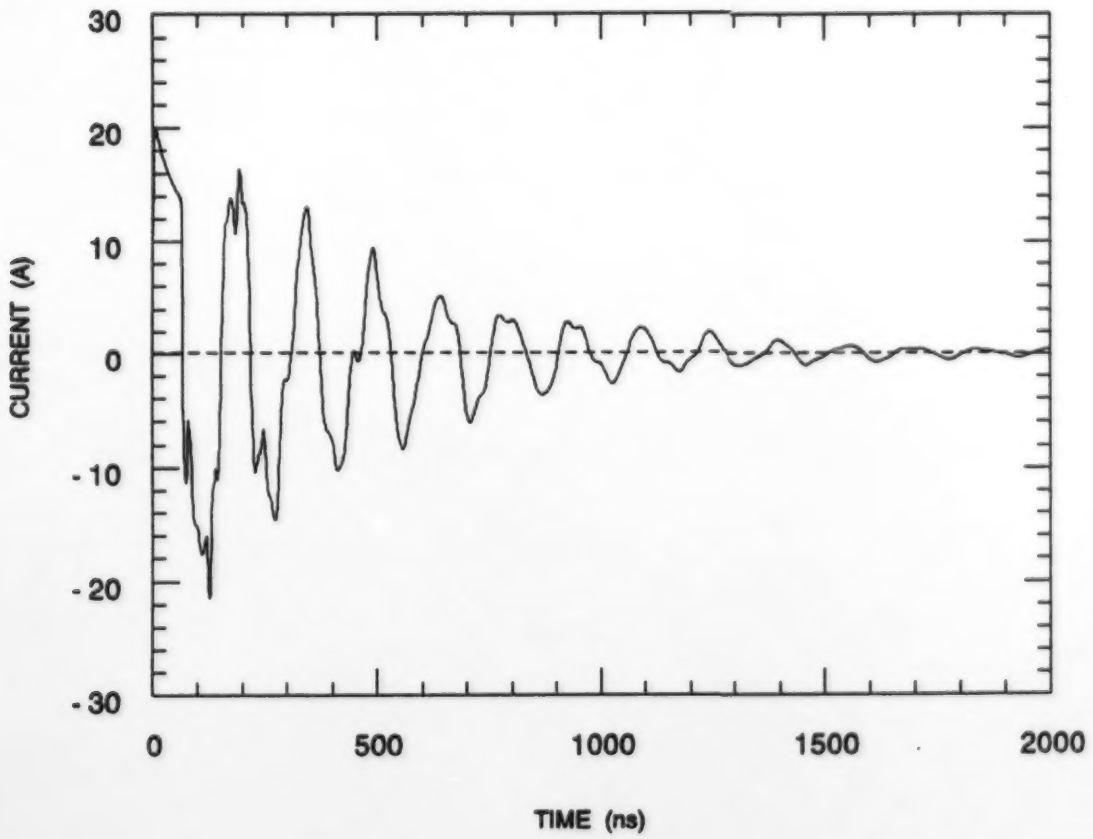

Figure 3-3 Calculated currents at the nose of the stick model helicopter induced from an incident EMP waveform, computed with NEC at 1024 frequencies, 0.25 MHz apart.

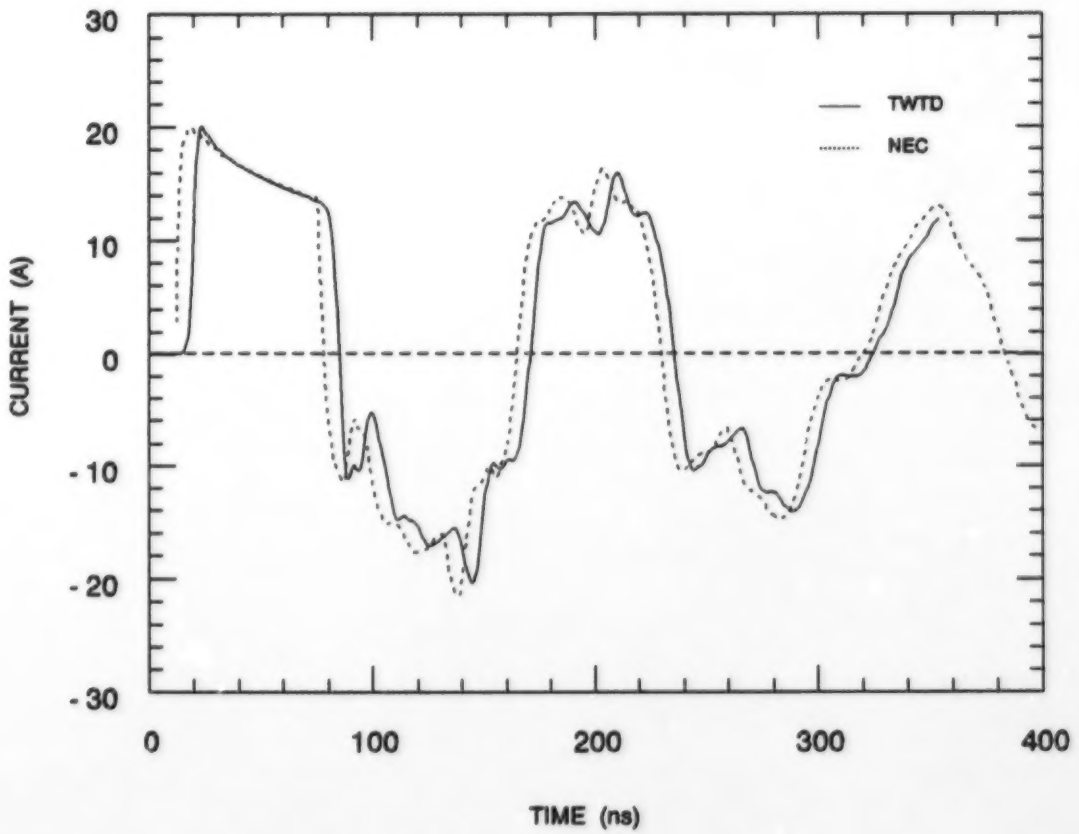

Figure 3-4 Current at the nose of the stick model helicopter induced from an incident EMP waveform calculated with NEC (slightly shifted) compared with the current calculated with TWTD.

discontinuity can introduce significant ringing and distortion in the solution.

A better expression, known as the *new* NATO definition, to approximate the EMP waveform is:

$$E(t) = AV \cdot \frac{e^{\alpha t}}{1+e^{(\alpha+\beta)t}} \qquad (14)$$

As shown in Figure 3-5, it has the same characteristics as the Bell curve (peak amplitude, rise time and pulse width), but its derivatives are now continuous over time and it has a more realistic leading edge. Note that the AV, α and β parameters are different from (12). The Fourier transform of (14) is:

$$E(\omega) = \frac{AV}{\alpha+\beta} \cdot \frac{\pi}{\sin(\pi \cdot \frac{\alpha-\omega j}{\alpha+\beta})} \qquad (15)$$

Figure 3-6 shows the frequency spectrum for both definitions as calculated with (13) and (15). The most important feature is that most of the energy is concentrated below 100 MHz with virtually nothing left above 500 MHz.

3.2 MINIMIZING THE COMPUTATION TIME FOR FREQUENCY DOMAIN CODES

In order to minimize the CPU time, two steps can be taken: reduce the number of segments or reduce the number of frequencies. For instance, NEC execution time grows exponentially with the number of segments or patches and consequently, keeping this number as low as possible will translate in considerable savings in CPU time. NEC guidelines state that segment length should be smaller than $\lambda/10$ at the highest frequency. By adjusting the segment length for the different frequencies, i.e. use longer segments at lower frequencies, it is possible to save up to 50% of CPU time. For example, modelling the helicopter by using a 63 segment model for frequencies up to 64 MHz and a 185 segment model for frequencies up to 256 MHz gives a saving of 22%. However, when varying the number of segments, it is important to keep the point of observation constant and to carefully look at the data to ensure continuity when passing from one model to another.

3.3 SELECTION OF AN ADEQUATE FREQUENCY STEP

The two important parameters that determine the number of frequencies are the frequency step (Δf) and frequency range (f_{max}). Figure 3-7 shows the effect of various frequency steps used in obtaining the time domain response. Obviously, if Δf is chosen too large, some important features of the frequency response such as the resonance peaks may be missed. As seen in equation (11), there is a direct relation between the frequency step and the time duration of the solution inherent to the inverse Fourier transform. If the Δf is chosen too large, the time duration of the solution (t_{max}) will be shorter than the response duration and the effect will be that the solution will not decay to zero. This can be observed in Figure 3-7 where the 4 MHz/step curve has a 250 ns duration and is obviously incomplete. In our example, the response duration is about 2 μs

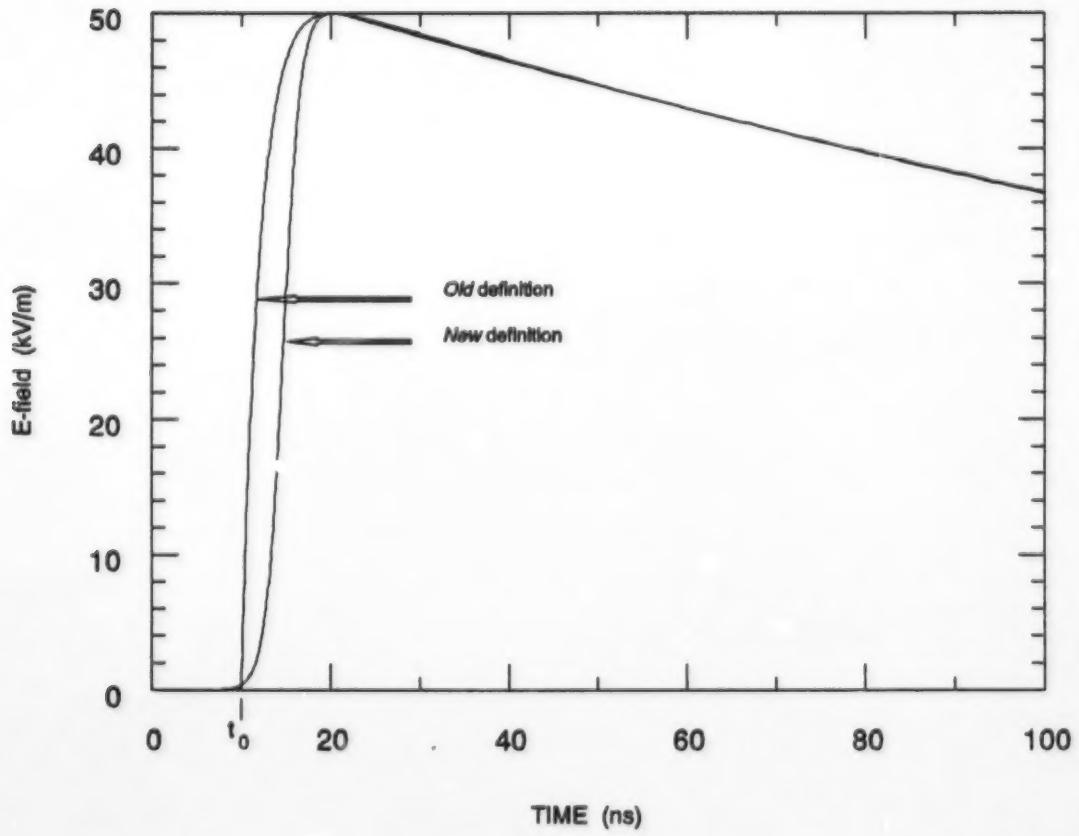

Figure 3-5 *Old* (double-exponential) and *new* (reciprocal) NATO definitions of the EMP waveform.

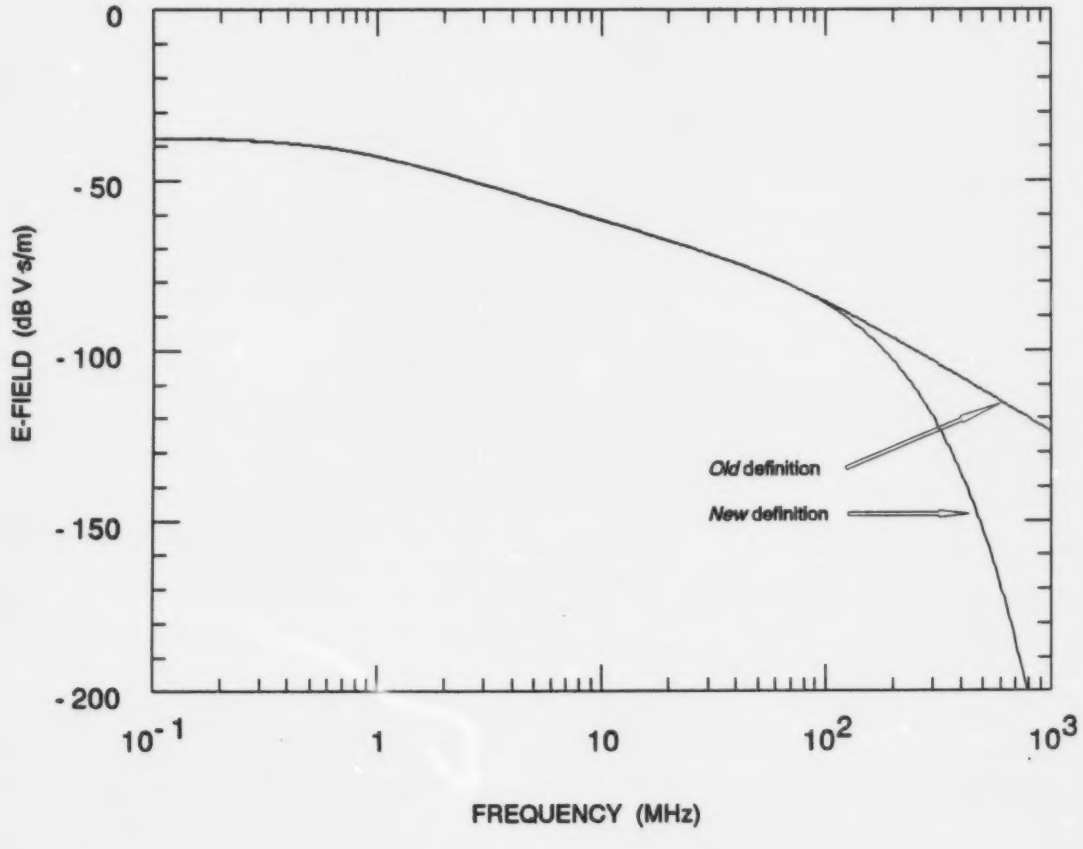

Figure 3-6 Frequency spectrum of *old* (double-exponential) and *new* (reciprocal) NATO definitions for the EMP waveform.

and therefore, a 0.5 MHz frequency step is adequate. It is also worth noting that there is no significant improvement when going from 0.5 MHz to 0.25 MHz step. An initial estimate of Δf can be obtained by estimating the first resonance of the structure from its the shape and dimensions. Starting with Δf approximately equal to $1/10^{th}$ of the estimated first resonance frequency is usually adequate. The length of the helicopter for instance is 19.5 m, which corresponds to a resonance around 8 MHz. A first estimate of the solution can be made by calculating the currents at 1 MHz steps.

3.4 SELECTION OF AN ADEQUATE FREQUENCY RANGE

The frequency domain simulation codes compute the solution at N frequencies, from Δf to $N \cdot \Delta f$[1], effectively ignoring the higher harmonics of the solution. A reduced frequency range results in more distortion (slower rise time, overshoot, etc.) due to the fewer number of harmonics included in the solution. It is easier to estimate what the proper range should be by plotting the solution $H(\omega) \cdot E(\omega)$ in the frequency domain as shown of Figure 3-8. From even a limited number of frequencies, calculated at a possibly larger Δf, it is possible to observe a tendency in the curve indicating that the higher frequencies contribute less and less to the solution. This is especially true for frequencies above 100 MHz where the frequency content of the excitation drops dramatically. Figure 3-9 shows the effect of the frequency range on the solution. A range of 32 MHz is obtained by rejecting the higher frequencies which contribute less than 10% of the peak resonance. This may be insufficient if a good estimation of the rise time or any sudden changes is desired, but may still provide an approximation of the solution. If the range is extended to keep the frequencies which contribute more than 1% of the peak, or about 100 MHz, the solution becomes much more accurate and only a slight overshoot and a slight distortion is observed.

3.5 INTERPOLATION OF THE FREQUENCY RESPONSE

It was shown that the selection of an appropriate frequency step and frequency range has a major impact on the accuracy of the response. It is also evident from the frequency domain response (Figure 3-2) that a smaller step should be used around the resonance peaks, especially around the first few peaks. However the standard application of the FFT algorithm requires that all frequencies be equally spaced, thus we would need to compute the currents at the same spacing for the entire frequency range resulting in an increase of the CPU time by the same factor.

To avoid this excessive use of CPU, a code was developed which takes a spectrum $H(\omega)$ consisting of unevenly spaced frequencies and, by using cubic spline interpolation, generates a new spectrum at evenly spaced frequencies at a different and possibly a smaller frequency step. This code allows us to use a smaller step only near the resonance peaks where the magnitude and/or phase change rapidly. Calculations in other regions can be made at a bigger step.

---

[1] The solution at DC is always 0, as the response to an incident field is function of its derivative.

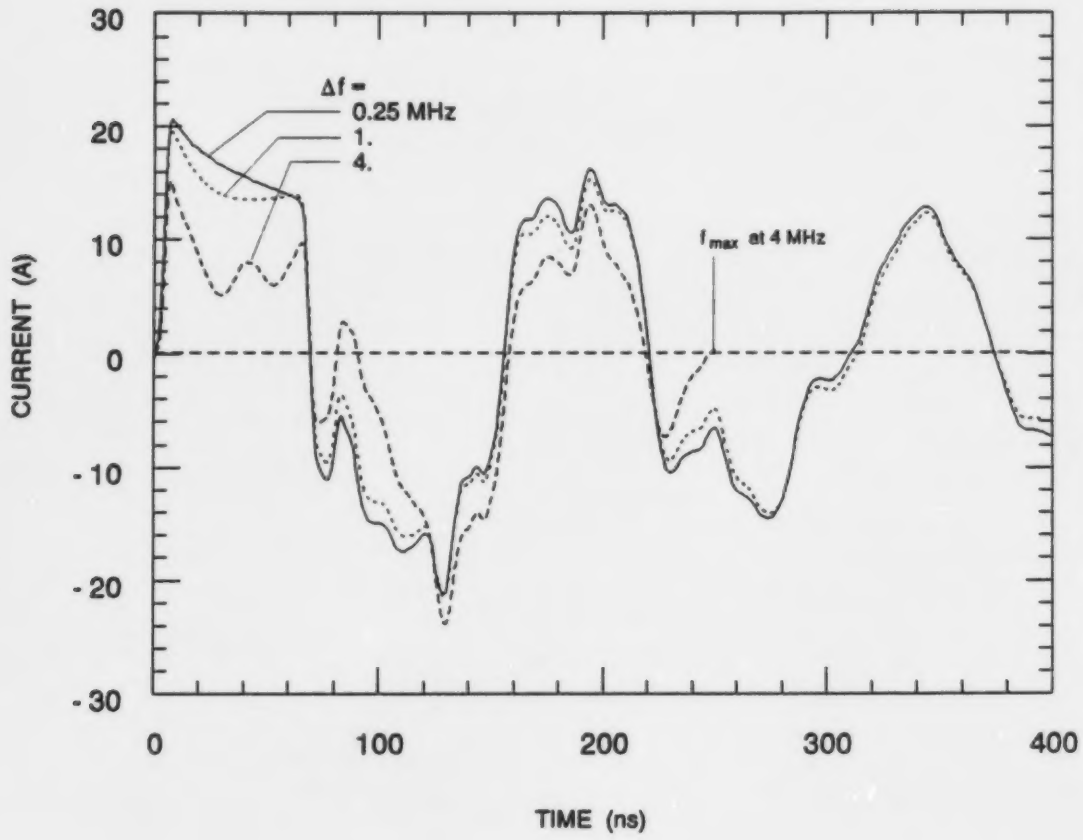

Figure 3-7 Effect of the frequency step on the time domain computed solution.

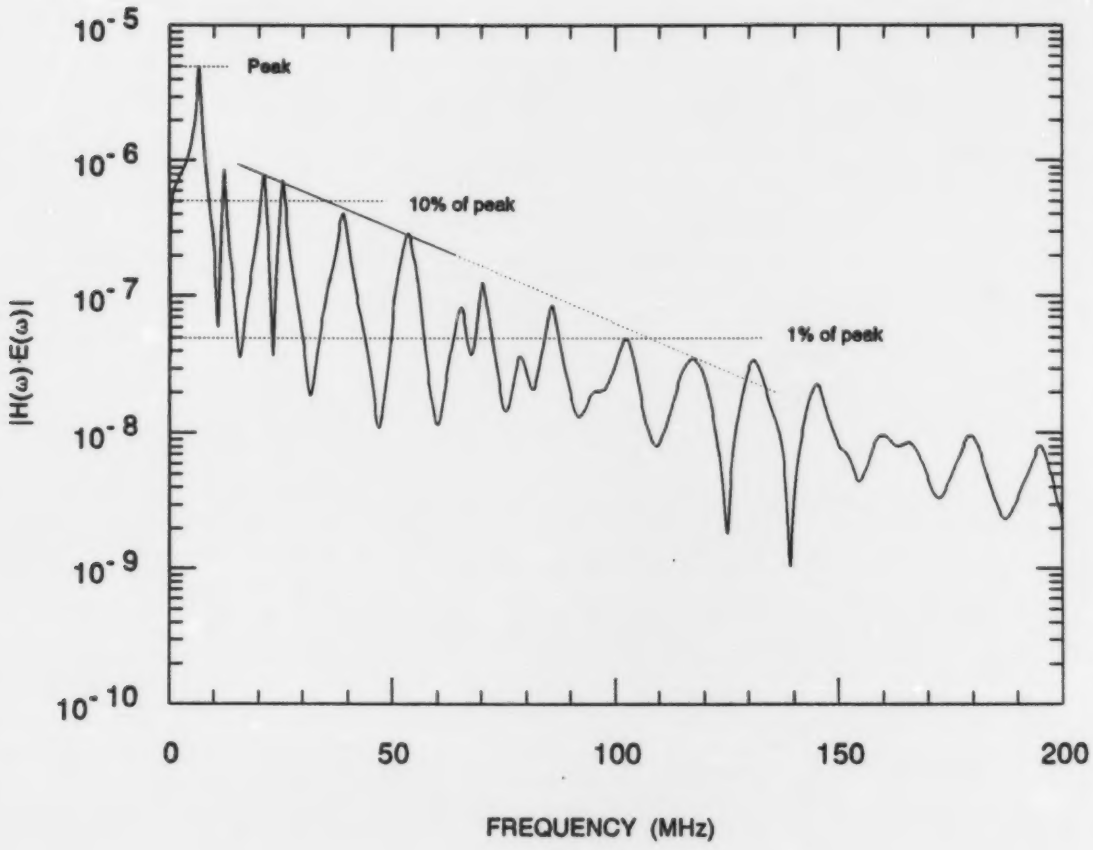

Figure 3-8 Product of the computed transfer function ($H(\omega)$) and the spectrum of the EMP excitation ($E(\omega)$).

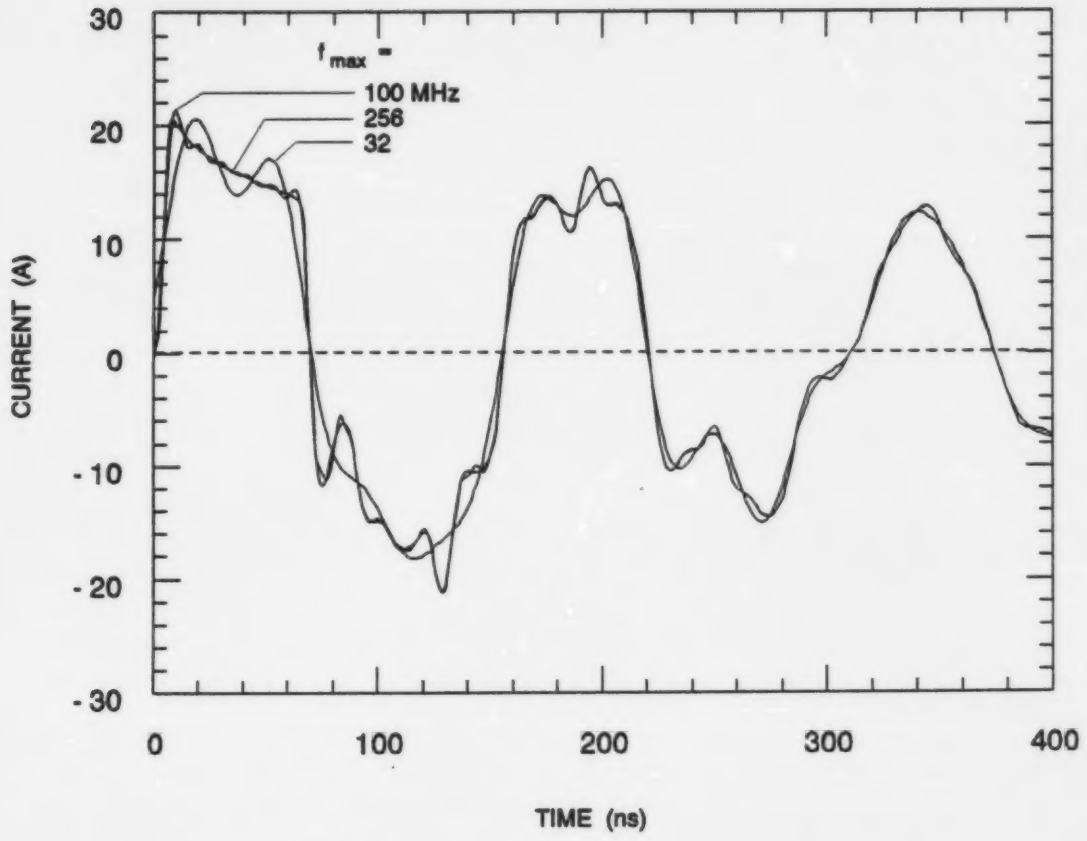

Figure 3-9 Effect of the frequency range on the time domain computed solution.

Spline interpolation and inverse FFT are then used to compute the time domain response.

The cubic spline routine used (CSAKM) is a part of the IMSL Math library [17]. It is based on a method developed by Akima and is designed to preserve the shape of the data and to minimize oscillations. The interpolation is performed on the magnitude and phase arrays, which have been sorted by arranging the frequencies in ascending order.

3.6 SMALL STRUCTURES

For small structures, ie. small compared to the wavelength of the highest frequency of the excitation, the first resonance occurs above the frequency range of the excitation. Frequency domain calculations can be made at a relatively few frequencies and interpolated at the intermediate ones because there are no abrupt changes below the first resonance.

It was observed on Figure 3-6 that a significant part of the energy of the EMP waveforms lies on the flat portion of the curve, below 1 MHz. When interpolating $Y(\omega)$ to perform the inverse transform, Δf must be small enough to take this portion of the spectrum into account.

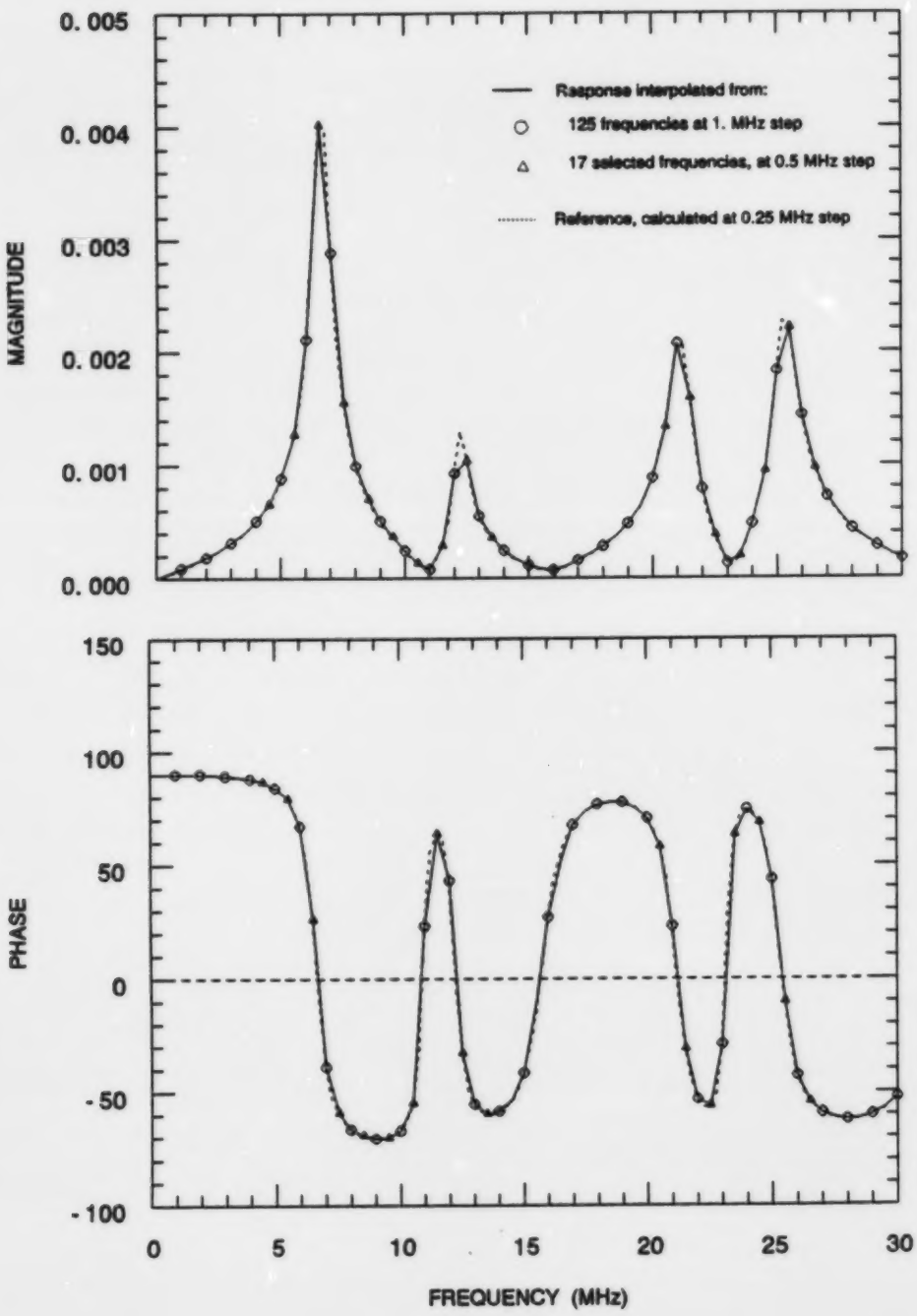

Figure 3-10 Frequency domain response at $\Delta f = 0.5$ MHz, obtained by interpolating the response at varying Δf.

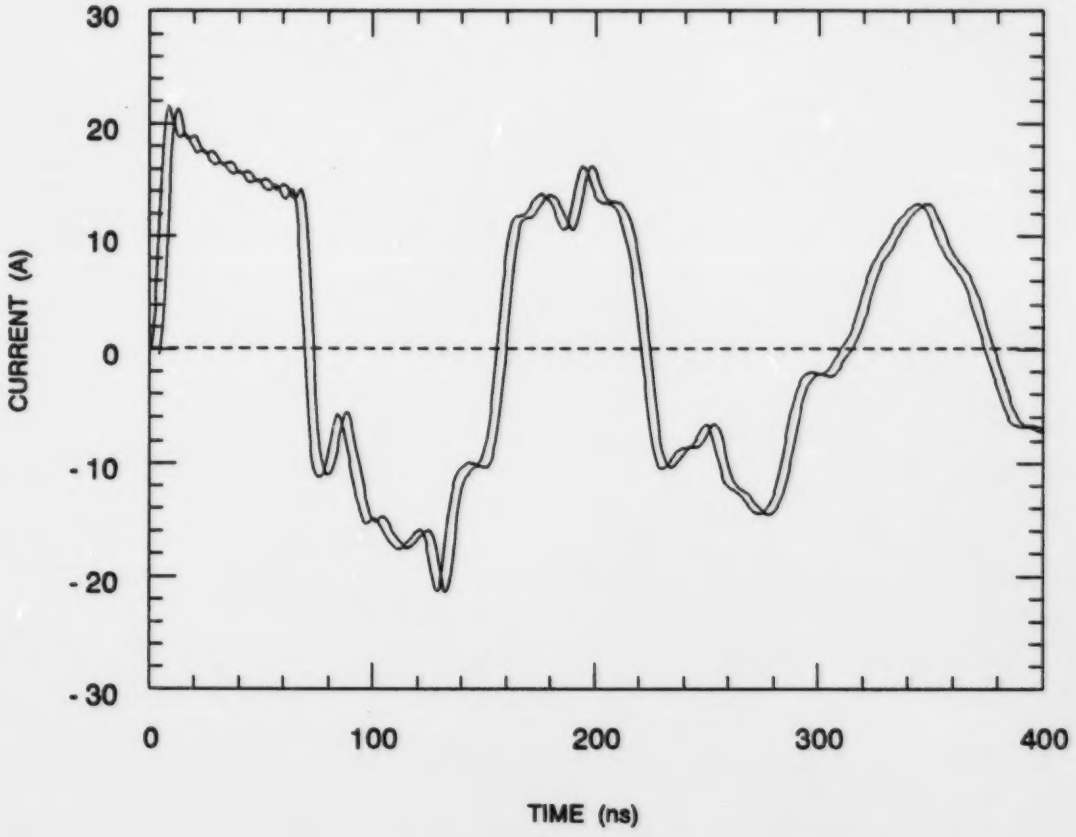

Figure 3-11 Solution obtained from standard application of the FFT (using 500 frequencies up to 125 MHz) compared with the solution (slightly shifted) obtained by interpolating 150 frequencies (up to 125 MHz, variable Δf).

4.0 CONCLUSIONS

It was shown that the use of numerical electromagnetic interaction simulation codes for predicting the response of complex systems to an incident EMP field is essential to the EMP analysis and hardening process. Although a variety of codes exist, both in time and frequency domain, one is often forced to use a time domain code due to the features or limitations inherent of each code.

A number of problems were solved with both time domain and frequency domain codes. It was demonstrated that the use of a frequency domain code can yield an accurate solution. Furthermore, very good agreement between different codes for solving a given problem was obtained.

It was also shown that the *old* NATO definition of the EMP waveform (double-exponential) is not appropriate and that the *new* definition (reciprocal) should be used.

Techniques were developed to reduce the excessive computer time required to obtain a time domain solution. It was shown that adjusting the model for different frequencies will save about half of the computer time. It was also shown that a judicious choice of the frequencies is important to produce an accurate solution with minimum computer time. A frequency domain interpolation technique was developed to further reduce the computer time. All the techniques developed can reduce the computer time by a factor of 7 to 10.

APPENDIX A

PROGRAM LISTING

```
*******************************************************************************
*
      Subroutine      FFT ( A, M )
*
*     Description:    Radix-2, in place Fast Fourier Transform
*                     To perform Discrete Fourier Transform
*
*                     This is the original algorithm from Cooley & Tukey
*                     taken from subroutine HARMM with the following changes:
*                      - Converted to Fortran-77
*                      - Use of entry points instead of control arguments
*                      - Scaling and phase corrected to conform with the
*                        definition of the DFT algorithm
*
*     Entry points:   FFT   ( A, M )          Direct FFT
*                     FFTS  ( A, M, DT )      Direct FFT, with scaling
*                     IFFT  ( A, M )          Inverse FFT
*                     IFFTS ( A, M, DF )      Inverse FFT, with scaling
*
*     Arguments:      A(*)    Complex array of data, input & output
*
*                     M       Log2 of size (size is 2**M)
*
*                     DT, DF  Time or frequency step
*
*******************************************************************************

      Implicit        Integer*4 (I-M)

      Parameter       (PI= 3.1415926535)

      Complex         A(*), U, W, T
      Real            DT, DF, Scale
      Logical         InvFFT                  ! Doing an IFFT ?

*******************************************************************************

*     Entry   FFT  ( A, M )

      InvFFt = .False.
      Scale  = 1.
      Goto 10

*****
      Entry   FFTS ( A, M, DT )

      InvFFt = .False.
      Scale  = DT
      Goto 10

*****
      Entry   IFFT  ( A, M )

      InvFFt = .True.
      N      = 2**M
      Scale  = 1./N
      Goto 11

*****
      Entry   IFFTS ( A, M, DF )

      InvFFt = .True.
      Scale  = DF     ! or = 1/N /DT
```

```
*******************************************************************************

   10 N    = 2**M
c     M = NINT(LOG10(REAL(N))/LOG10(2.))

   11 NV2 = N/2
      NM1 = N-1
      J   = 1

      If ( Scale .ne. 1. ) Then                  ! Scale
         Do 21, I= 1, N
   21       A(I)=A(I)*Scale
      Endif

                                                 ! Bit_reverse input data
      Do 20, I= 1, NM1
         If ( I .lt. J ) Then
            T   = A(J)
            A(J)= A(I)
            A(I)= T
         Endif

         K = NV2

   15    If ( K .lt. J ) Then
            J = J-K
            K = K/2
            Goto 15
         Endif

         J = J+K
   20 Continue


      Do 40, L= 1, M
         LE  = 2**L
         LE1 = LE/2
         U   = (1.0,0.)
         W   = CMPLX( COS(PI/LE1), SIN(PI/LE1) )
         If ( .Not. InvFFT ) W = CONJG(W)    ! Adjust phase if FFT
         Do 40, J= 1, LE1
            Do 30, I= J, N, LE
               IP   = I+LE1
               T    = A(IP)*U
               A(IP)= A(I)-T
               A(I) = A(I)+T
   30       Continue
            U=U*W
   40 Continue

      Return
      End
```

APPENDIX B

GUIDELINES SUMMARY

Guidelines developed in this report are summarized herein. The primary objective was to minimize the CPU time required to run the interaction codes and still obtain an accurate solution.

B.1 GUIDELINES FOR SOLVINS TIME DOMAIN PROBLEMS

A numerical electromagnetic interaction code is used to compute the currents or charges at multiple discrete frequencies. These frequencies need not be evenly spaced and interpolation can be used to obtain an evenly spaced sequence necessary to compute the inverse Fourier transform. Judicious choice of frequency step and frequency range may considerably reduce the computer time.

a) Use a realistic model for the excitation with a known expression of its Fourier transform, such as equation (15).

b) Use longer segments and larger patches at lower frequencies to reduce the problem size.

c) Estimate the first resonance peak from the dimensions and shape of the object. Start with Δf equal to approximately $1/10^{th}$ of the estimated first resonance.

d) An incomplete time domain solution, $y(t)$, suggests the need for a smaller Δf, especially near the resonance peaks.

e) The higher frequencies of $Y(\omega)$ will contribute less and less to the solution. Therefore, it is possible to identify that trend in the product $H(\omega)\cdot E(\omega)$ to estimate a proper value for f_{max}. Very good results are obtained when the higher frequencies contribute less than 1% of the peak resonance.

f) The Δf used to compute the inverse transform (after interpolation) should be small enough to cover the lower frequency characteristics (flat portion of the spectrum on Figure 3-6) of the excitation. For the standard NATO EMP waveform definition, Δf should be smaller than 1 MHz.

B.2 GUIDELINES FOR INTERPOLATING THE FREQUENCY DOMAIN TRANSFER FUNCTION

A cubic spline routine (CSAKM) from the IMSL Math library is used to interpolate the frequency domain solution computed at unevenly spaced frequencies and obtain a sequence at evenly spaced frequencies.

a) Convert the complex sequence into two real sequences representing its magnitude and phase.

b) If necessary, add the DC value (f=0). In this case, the magnitude will be 0 and the phase ±90°.

c) It is necessary to unwrap the phase before the interpolation can take place.

d) Perform the interpolation and convert back to real and imaginary arrays.

B.3 GUIDELINES FOR PERFORMING THE DFT AND FFT ALGORITHMS

The application of the DFT algorithm requires that the N point complex sequence be calculated at evenly spaced frequencies.

a) Multiply the sequence with a window, such as a cosine-tapered window, if a significant discontinuity is observed at the higher frequencies because of the limited number of frequencies computed.

b) Extend a N point sequence to M point by adding zeroes at the end. This produces a better interpolation of the solution, which is particularly useful for plotting, and also allows the use of the more efficient FFT algorithm which may have restriction on the size of the sequence.

c) Mirror the M point sequence with its conjugate, thus forming a 2M point sequence, on which the FFT will be performed. The real part of result will be the solution (the imaginary part will be zero).

d) Include the effect of the scaling property of the Fourier transform as defined in equation (9) into the FFT algorithm.

e) Use the equations (10) and (11) to compute Δt and t_{max} from Δf and f_{max}.

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DFT
Discrete Fourier Transforms
FFT
Fast Fourier Transform
NEC
Numerical Electromagnetic Code